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October 2000

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IDA Paper P-3482

Log: H 99-001572

This work was conducted under contract DASW01 98 C 0067, Task Assignment DA-2-205, for the Defense Advanced Research Projects Agency/Electronics Office. The publication of this IDA document does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official position of that Agency.

INSTITUTE FOR DEFENSE ANALYSES

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PREFACE

This paper was prepared for the Defense Advanced Research Projects Agency/Electronics Technology Office in partial fulfillment of a task entitled Microelectromechanical Systems (MEMS) Development and Insertion.

ACKNOWLEDGMENTS

No paper is ever truly the result of a single individual's efforts. The author wishes to acknowledge important contributions by IDA colleagues Dr. Richard Singer, Task Leader, DoD MEMS Transition Task, Dr. Arun Seraphin, and Mr. Andrew Calhoun for their inspiration, encouragement, and support during the data-collection phase of the work resulting in this paper.

Colleagues Dr. Michael Rigdon, Dr. William Hong, and Dr. Lisa Veitch made helpful comments on earlier drafts.

While the author benefited immensely from the assistance provided by colleagues, he alone is responsible for any errors of fact or judgment contained in the following paper.

MEMS Technology Transition Opportunities for Gas Turbine Engines

Presentation to the IGTI TurboExpo
Indianapolis, Indiana,
June 9, 1999,
by

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The views expressed are those of the author and do not necessarily reflect the views of either the Defense Advanced Research Projects Agency, the Department of Defense, or the Institute for Defense Analyses

The following presentation is based on a workshop conducted jointly with the Propulsion Directorate of the Air Force Research Laboratory, with participants drawn from the Navy, Army, and NASA gas turbine engine development community. The workshop was held in Dayton, Ohio, on May 21 and 22, 1999. The workshop was conducted as part of the Institute for Defense Analyses' task on behalf of the Defense Advanced Research Projects Agency for the purpose of assisting DARPA in identifying opportunities to transition microelectromechanical systems (MEMS) from the laboratory to the field.

The workshop attempted to identify areas of gas turbine engine technology, as well as integration points where MEMS technology might make a significant difference in the overall performance of an entire system, be it a vehicle, a power-generation facility, or a support component in a larger system (e.g., an auxiliary power unit).

As noted above, the views expressed in the following charts are those of the author and do not necessarily reflect the views of the Department of Defense, the Institute for Defense Analyses, or attendees at the May 21/22, 1999, workshop.

Gas Turbine Engine Technology Objectives

- Improve Thrust-to-Weight Ratios
- Improve Fuel Efficiency
- Reduce Maintenance Costs
- Reduce Development Costs/Time

The workshop participants represented DoD and NASA organizations involved in the development of future gas turbine engines primarily for aircraft applications. Participants stepped back from their day-to-day responsibilities to consider where they anticipated government requirements to be some 10 to 15 years from now. The broad goals noted above were intended to elicit concepts for improved or new gas turbine engine technology that would be substantially beyond the goals sought by the Integrated High Performance Gas Turbine Engine Program.

Technical Challenges I

- Improve Thrust-to-Weight Ratios
  - Improve Global Environment Sensing (outside and within engine)
    - Improve algorithms that relate empirical data to engine performance
  - Reduce Engine Weight
  - Expand Use of Active Controls
  - Allow Engine Operating Temperatures to Approach Theoretical Material Limits
    - Alternative methods for cooling
      - Critical engine components
      - Engine electronics
  - Ice Detection, Characterization, and Deicing

To obtain these objectives, the workshop participants identified several technical challenges that must be overcome. The next four charts call out several goals and associated challenges facing developers of new turbine engines. With perhaps the exception of the challenge of ice detection, characterization, and deicing, the workshop participants felt that these challenges were not specific to aircraft applications of gas turbine engines. As will be noted below, success in meeting any of these challenges for aircraft gas turbine engines would have substantial benefit for gas turbine engines used in marine, land vehicle, and mobile or stationary power generation applications.

Participants noted that MEMS technology, in principle, affords opportunities to gather data about engine performance and environment comparable in quality to data gathered by non-MEMS sensors, at equal or lower cost, with greater reliability, greater redundancy, and greater accuracy, given the ability to combine processing with sensing and other functions. But what is perhaps the most exciting facet of MEMS technology is the opportunity to gather data about engine performance and operating environments that could not previously be collected. MEMS and other microsystems technologies offer engineers and scientists opportunities for new paradigms that may lead to significant breakthroughs in our understanding of gas turbine engine performance and cost drivers.

The technical goals and challenges need to be addressed from both performance and cost perspectives to take greatest advantage of MEMS technology.

Technical Challenges II

- Improve Fuel Efficiency
  - Improve Combustor Controls
  - Improve Fuel Supply Controls
  - Increase Operating Temperatures
    - Active cooling of critical components
      - Alternatives to fuel, bleed air cooling
    - Use of high-temperature electronics

The role MEMS technology can play in meeting the technical challenges identified is not entirely obvious. Active controls were identified by workshop participants as a key technology to meet the challenges of greater thrust per pound, higher operating temperatures, and more efficient cooling of critical engine components. Active controls are also important to meet the challenges that stand in the way of improving fuel efficiency.

But workshop participants recognized that meeting technical challenges to improved gas turbine engines may not mean inserting MEMS technology into the engines themselves. MEMS technology may have a near-term, highly beneficial role to play in improved test and evaluation, instrumentation, quality control/quality assurance on the production floor, and in other facets of the gas turbine engine technology base, rather than in or on the engines themselves.

Technical Challenges III

- Reduce Maintenance Costs
  - Engine Health Monitoring
    - Real-time sensing, feedback, and control
    - Stored sensor information for use in diagnostics and repair
  - Fault Detection, Classification, and (Ideally) Repair
    - Control systems
    - Fuel systems
    - FOD
    - Ice

Workshop participants expressed the view that MEMS technology could play a very large role in providing improved knowledge of the processes by which engines age and require maintenance. A great deal of additional thought is required, however, to identify specific engine areas or subsystems suitable for MEMS technology insertion.

MEMS technology could be used to better understand failure modes and effect so that improvements could be made. For example, one might consider inserting MEMS or other sensors throughout the turbine engine oil subsystem, turbine engine hydraulics, and even turbine engine electrical systems for the purpose of merely monitoring and reporting the actual functions, performance, and environmental stresses encountered in these systems. The development of historical data bases would allow substantial improvements in identification of trends or even specific event signatures, which could be tied to requirements for either preventive or even major repair maintenance activities.

Technical Challenges III (cont'd.)

- Reduce Maintenance Costs
  - Blade and Disk Crack Detection and Assessment
    - Real-time crack detection and assessment
      - Sensors for harsh environments
      - Algorithms to relate empirical data and analytical constructs for improved understanding of failure modes and effects
    - Improved real-time fan blade position monitoring and tolerance control
    - Improved manufacturing process control for turbine blades
  - Extend Combustor Life

MEMS technology is already being used in some sensors associated with turbine disk and fan blade inspections. For example, MEMS-based sensors are being used for post-failure analysis and in-service inspections during depot maintenance.

It is possible that MEMS-based sensors could be used to do fan blade and turbine disk manufacturing process inspections and/or industrial process control, thereby reducing maintenance costs by helping parts suppliers and engine manufacturers eliminate failure-prone components from the final stages of engine assembly, manufacture, test, or operation.

The interest in developing real-time fan blade condition monitoring sensors, as well as the ability to monitor the exact position of the fan blades within the engine, is quite keen. For the foreseeable future, it appears that the harsh environment of the gas turbine engine will make this challenge almost insurmountable, at least for sensors that can be affixed with an adhesive to fan blades or fan disks found within the hot sections of the engine. Use of optical sensors to provide information on turbine blade tip clearance, turbine blade pitch, etc., might be feasible, depending upon the specific location to which the sensor must be affixed, the modes of data reporting and storage, and other environmental factors.

MEMS technology may have a significant role to play in the manufacture and use of combustors.

Technical Challenges IV

- Reduce Development Costs/Time
  - Algorithms Describing Environment/Engine Interactions and Sensors to Collect Required Data
  - Algorithms Describing Failure Mode/Effects for Turbine Blades, Turbine Disks, and Sensors to Collect Required Data
  - Revised T&E Protocols
    - Telemetry instrumentation permitting "snap-in/snap-out" deployment of developmental engines in test rigs

One of the largest challenges facing the turbine engine technology base is the need to accelerate engine development and reduce its cost. The workshop participants felt that a number of steps outlined in this chart would be beneficial.

In the near term, the development and implementation of standards to transition communication of sensors to test cell instrumentation from wired to wireless would probably make the largest contribution to developmental engine cost reduction. Many of the technologies associated with this transition benefit from MEMS technologies but are not uniquely dependent upon MEMS devices or MEMS/microsystems technology manufacturing processes. Wireless MEMS sensors, radio frequency (RF) MEMS, and MEMS sensors capable of operating in harsh environments will make significant contributions here, but even the shift from wired sensors terminating at an engine-mounted communications station (which handles data transfer from engine) to test-cell instrumentation without wires would be a substantial leap forward.

Both standards for "plug-and-play sensors" as well as "snap-in/snap-out" developmental engines and test cells will benefit from MEMS technologies. Further gain will occur if new algorithms can specify and use sensor data acquired as a result of unique MEMS/microsystems technology attributes. Workshop participants opined that much creative work remains to be accomplished.

Matching MEMS Applications to Technical Goals and Challenges

- Domains
  - Operating Engines
    - Aircraft/UAV
    - Ground vehicle/SES
    - Naval vessels
    - APUs/Stationary power
  - Developmental Engines
- Technology Barriers
- Correlated Activities

IDA's task is to assist DARPA in transitioning MEMS technology from the laboratory to the field. As we look at the gas turbine engine technology base, we see very significant differences in the domains in which the MEMS and microsystems technology might operate, as well as very specific applications. There are substantial differences in the level of maturity and robustness of MEMS and microsystems technology required to support research and development, test and evaluation, or manufacturing and maintenance activities compared to that required when putting MEMS or microsystems technologies in operating engines. Even within an operating engine environment, there appear to be important differences in inserting MEMS technology within the engine core versus its supporting infrastructure such as oil systems, hydraulics, electrical systems, and supporting mechanical structures. There may also be significant differences in the suitability of MEMS technology based on turbine engine applications—in aircraft and UAVs versus ground vehicles, surface effect systems, maritime systems, auxiliary power units (APUs), and stationary power sources.

There are a number of significant technology barriers standing between the laboratory and the field that must be addressed. And, as suggested earlier, it is important to understand what MEMS technology can provide to the scientific and engineering community involved in supporting all facets of the gas turbine engine technology base and to take best advantage of these unique capabilities. In the balance of the presentation will attempt to look at these issues.

Assessing Technology Transition Opportunities I

- Application Regime
  - Laboratory-Scale R&D
  - Engine Test and Evaluation
  - Manufacturing and Maintenance
  - Deployment in Operational Engines
- Engine Applications
  - Aircraft/UAV
  - Land Vehicles/SES
  - Naval Vessels
  - APUs/Stationary Power Systems

Workshop participants considered whether the regime in which MEMS technology would be used or the specific engine application of interest would make a difference in the speed and relative ease of MEMS technology insertion. We looked at the differences and distinctions in the regimes and specific engine applications noted here.

Assessing Technology Transition Opportunities II

- Laboratory-Scale R&D
  - Environment Characterization
  - Benign to Moderately Challenging Environments
  - Self-Calibration
  - Small Number of Products
- Test and Evaluation
  - Environment/Engine Characteristics and Performance
  - Engine/Subsystem Controls
  - Telemetry
  - Benign to Demanding Environments
  - Moderate Number of Products

When we looked at laboratory-scale R&D, we found that the environments are relatively benign and that the issues of interest are really how to characterize the environments in which gas turbine engines and components are operated. Workshop members expressed the importance of self calibration and pointed out that the number of products acquired would probably be fairly small.

Moving from the laboratory to test and evaluation, we concluded that a very substantial market exists here. The Propulsion Instrumentation Working Group has suggested that as much as 30–35 percent of the dollars associated with developing new engines can be related to instrumentation. There should be tremendous interest in the use of MEMS and microsystem technologies to reduce the labor hours, technical challenges, and frustrations of instrumenting developmental engines. Although the developmental engine environment is very challenging, it does not require the same durability of sensors, connectors, and data-recording components as an operating engine. Furthermore, the number of sensors and associated infrastructure for test and evaluation (T&E) applications, when combined with sensors to support R&D activities, might be sufficient to create a small but viable market. To the extent that MEMS technology to support gas turbine engine R&D and T&E can be generalized to other RDT&E activities, the opportunity to transition MEMS technology improves dramatically.

Assessing Technology Transition Opportunities III

- Manufacturing and Maintenance
  - Manufacturing and/or Maintenance Process Control
  - Challenging Technical and Legal Environments
    - Liability issues
  - Standards for Calibration, Reliability, Durability, Failure Modes and Effects
  - Larger Number of Products
- Operational Engines
  - Control Systems, Engine Health Monitoring, “Smart” Engine Operations, Real-time Diagnostics and Repairs…
  - Harsh Environments
  - Standards Throughout
  - Very Large Number of Products

The use of microsystems technologies and MEMS in manufacturing and maintenance looks very promising. In particular, there are opportunities to use MEMS technology to improve manufacturing processes and quality assurance. Ascertaining materials properties at the conclusion of each step in the fabrication of turbine disks and turbine blades may be an early and highly leveraging, cost-effective use of MEMS technology for the industrial base. Use of MEMS-based nondestructive inspection (NDI) tools to examine gas turbine engine components and associated subsystems and structures may be another high-payoff application.

It is important to bear in mind that component failures in engine lubrication systems, hydraulic systems, electrical systems, electronic control systems, and support structures play major adverse roles in the economical operation of systems which depend upon gas turbine engines. From an operator’s perspective, knowing the condition of the entire gas turbine engine power train is no less important than knowing the condition of the engine core itself. Employing MEMS technology to improve manufacturing processes, quality assurance, and maintenance practices throughout the power train may be as economically important as inserting MEMS technology into the engine core itself.

MEMS Technology Development

- High-Temperature Materials for Use in MEMS Devices
  - Operating Temperatures Are at Extreme Edge and Beyond for Current MEMS Device Materials
- MEMS Manufacturing Processes
- MEMS Test, Calibration, Reliability, Durability Issues
- Packaging and Integration Issues

Workshop participants tried to step back from a narrow focus on the development of new gas turbine engines for aircraft to determine whether other applications would face different challenges or encounter different transition barriers. We concluded that the challenges, barriers, and opportunities for MEMS technology insertion did not change in any fundamental way.

The specific technical challenges confronting the MEMS development community and identified here must be addressed if MEMS devices can be integrated into products that will be successful in the marketplace of the gas turbine engine technology base.

Correlated Challenges

- Algorithm Development
  - Matching Voids in Theoretical and Analytical Understanding with New Sensors to Collect Data to Fill Voids in Knowledge
- Technology and Business Maturation

Workshop participants really drove home the point that MEMS technology could make very significant differences if the technology could be used to gather data that is not now available through other sensor systems. Building sensors and algorithms together appears, to the workshop participants at least, to be the area in which major economic and technological progress will be made.

Workshop participants also stressed the importance of quickly maturing MEMS and other microsystems technology, along with the associated business practices. Standardized interfaces among MEMS devices and between MEMS and non-MEMS electronics, communi-cation systems, data-recording systems, etc., are crucial to the transition of MEMS device-level technologies to the field. Improved understanding of MEMS and traditional electronics as well as mechanical solutions to engineering problems is also required if the MEMS community hopes to overcome acquisition system biases against new technology.

These issues are addressed in more detail below.

MEMS Devices and *Potential* Applications I

IDA's Preliminary Composite Assessment

MEMS Device and/or Process	Global Environment Sensing	Active Controls	Active Cooling	High-Temperature Electronics	Ice Detection	Combustor Components and Controls	Fuel Supply Controls
Pressure	+++	+++			++	++	++
Flow	+++	+++			+	++	+++
Temperature	+++	++	++	+++	+	++	+
Force/Strain	++	+++			+		+
Magnetic							
Acceleration	++	+			+	+	+
Electro-optical	++	++			++		
Rate	++	++	+			++	++
Position		+					
Acoustic/Vibration	++	+++	+		++	++	+
Heaters		++	+			+++	
Power MEMS	+	++	++	+		++	++
Microfluidics		+	+++				+
Aerodynamics Hydrodynamics	++	++	+			++	++
Force Transducers	++	++	+		+	++	+
Data Storage	+++	+	+	+	+	++	++
RF MEMS							
Optical MEMS							
MEMS Fabrication	+	+	+	++		++	+

This chart and the one that follows represent IDA's preliminary assessment of future MEMS technology applications in the gas turbine engine technology base. The charts combine tentative judgments about technical maturity, technological risk, and economic payback.

Three pluses represent areas of technology where in our judgment gains could be made to greatest economic or technical benefit, albeit perhaps on a longer timescale and at greater technological risk. Two pluses suggest that gains could be made relatively near term with some considerable economic benefit. One plus suggests that MEMS technology applications could be undertaken relatively soon, although probably not in the most harsh environments, with some presumed economic or technical benefit.

Empty cells in these matrices reflect ignorance of potential applications and/or payoffs *or* a judgment that MEMS technology is not likely to be usefully applied in the next 10 to 15 years.

I wish to emphasize that these judgments are preliminary and tentative. IDA staff arrived at these judgments based on a rather naive and cursory synthesis of literature reviews, discussions with MEMS technology developers, and discussions with gas turbine engine technology developers and other experts. Comments, criticisms, and substantiation of these judgments or alternatives are most welcome.

MEMS Devices and *Potential* Applications II:
IDA’s Preliminary Composite Assessment

MEMS Device and/or Process	Engine Health Monitoring	Fault Detection, Classification and Repair	Blade and Disk Crack Detection	Extended Combustor Life	Engine/Environ-ment Algorithm and Sensor Development	Blade and Disk Failure Algorithm and Sensor Development	Engine Telem-etry for “Snap-in/Snap-Out” Testing
Pressure	+++			++	+++		
Flow	+++			++	+++		
Temperature	+++	+	++	+++	+++	++	
Force/Strain	++	+	++		+++	++	
Magnetic		++	++	+	++	++	
Acceleration	++	+++	++		++		
Electro-optical	++	++	+		+++	++	+
Rate	+		+	+	+	+	
Position	+	++	++		++	++	
Acoustic/ Vibration	+++	++	++	+	+++	+++	
Heaters		+	+	+	+	+	
Power MEMS	+	++					++
Microfluidics		+		++		++	
Aerodynamics Hydrodynamics	+++	+	++	++	++	++	
Force Transducers	++	+	++	+			
Data Storage	+++	++	+++				
RF MEMS	+++	+					+++
Optical MEMS	+++	+	+++	+			+++
MEMS Fabrication		++	++		+++	+++	

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This chart is a continuation of the preceding chart.

Transition Barriers I

- Acquisition Perspectives
- Government Acquisition Processes
- Technological and Business Maturity
  - Manufacturing Issues
  - Integration
  - Business Practices

The workshop participants identified several important areas which constitute barriers to the transition of MEMS and microsystems technologies from laboratory to field application. These are discussed in more detail below.

Transition Barriers II

- Acquisition Perspectives
  - Government, Prime Contractors Seek System-Level Solutions
- Acquisition Process
  - Requirements Process Reinforces Bias in Favor of Systems vs. Devices, Subcomponents, or Subsystems
  - Acquisition Process Relies Heavily on Non-Government Standards and Specifications; Bias Favors Established Technologies
  - Acquisition Process Places Premium on Technology Demonstrations and Rapid Prototyping; Demonstration of "Fieldable Prototypes" or Working Models

Perhaps the biggest current barrier to successful MEMS transition is the difference between the buyer's and the developer's view of technology.

The government and its prime contractors are interested in solutions that solve system-level problems. MEMS and microsystems technology developers offer individual products or devices. The failure to relate a problem to a device-level solution (the buyer's perspective) or a device-level approach to a system-level problem solution (the MEMS technology developer's perspective) is a huge barrier to technology transition. Buyers want solutions to system-level performance challenges and are, to first order, indifferent to the underlying technologies that result in desired performance, cost, and cycle times; maintenance hours and maintenance costs; reliability, etc.

Furthermore, the acquisition process by which the government works is heavily biased in favor of existing technologies, as noted here. It is prejudiced against technological risk in favor of predictability in schedule and cost. The metacosts associated with uncertainty in the performance of new technologies and the implications of such uncertainty for cost and schedule are so high, technology insertion becomes virtually impossible.

Advanced technology demonstrations (ATDs) and advanced concept technology demonstrations (ACTDs) are an attempt within DoD to "buy down" these prohibitively high "metacosts," but to be successful, MEMS technology developers must convince the ATD/ACTD managers in government and industry to take substantial risks. This can be done, but persuasive cases must be built by the MEMS technology developers.

Transition Barriers III

- Technological and Business Maturity
  - Manufacturing
    - Device quality
    - Repeatability
    - Manufacturing cost drivers
  - Integration
    - Packaging
    - Productization
  - Business Practices
    - Matching customer needs
    - Disseminating salient and relevant technical information
      - Reliability, accuracy, durability, failure modes and effects, cost and cost drivers
      - Calibration processes, testing protocols, and user manuals

MEMS and other microsystems technology developers have yet to demonstrate the technical maturity of their competitors. For example, MEMS developers rarely describe the outcomes of manufacturing in terms of device quality, process yield, repeatability, reliability, or performance accuracies on a large sample or population basis. Furthermore, MEMS technology developers rarely identify manufacturing process cost drivers—are costs sensitive to quantity ordered, materials and processes used in manufacture, testing and qualification, or all of the above?

Packaging, productization, and integration of MEMS devices into larger systems remain very substantial issues. MEMS devices compete with alternative concepts and often lose market ground because the individual devices cannot be readily integrated into larger arrays or subsystems, even though competing devices do not perform as well on a cost-per-calculation or cost-per-function basis.

Finally, the business practices of any of the MEMS developers reflect tremendous enthusiasm for science and technology that is not always sensitive to the needs of customers, clients, and consumers. More thorough and careful documentation of experiments; testing and qualification of MEMS devices; full and complete assessments of reliability, failure modes and effects, as well as cost drivers, will make transition of MEMS technology easier to accomplish because would-be consumers will have a much more complete picture of MEMS technology strengths for their applications.

MEMS in Turbine Engines: Future Prospects

- Are the technical goals and challenges reasonable?
- Are the most reasonable MEMS/Micro-systems Technology areas highlighted?
- Are there demonstrable MEMS devices/ products available for detailed engineering evaluation to aid in further development of gas turbine engine technology?

The foregoing presentation represents a summary of conclusions and judgments reached by a small panel of government gas turbine engine technologists who tried to understand how MEMS technology might play in the future. Our goal in organizing this workshop was to identify potential applications of MEMS technology in the gas turbine engine industrial base, barriers to the transition of MEMS technology, and some remedial actions that could be taken to overcome these barriers.

This chart represents our challenge to you, the reader. It is an open invitation for you comment on the workshop results reported herein.

Future IDA Workshop

- First week of August at IDA
- Additional Government-Only Session
- Feedback from Industry and Academia
- Limited Opportunity to Present Well-Documented Examples of MEMS Technology Applied to Gas Turbine Engine Challenges

We invite your comments on these charts. Furthermore, we invite you to do so in person as follows:

There will be a workshop held in the first week of August here at IDA. We hope to spend the afternoon of Monday, August 2, 1999, with representatives of the U.S. Government gas turbine engine community once again to see whether the workshop results reported here truly scale across regimes and applications of gas turbine engines.

We would like to spend portions of Tuesday and Wednesday, August 3 and 4, collecting feedback from industry and academia. Not only do we hope to hear from organizations involved in the development of gas turbine engines, we would like to hear from their customers—airlines, aircraft manufacturers, and ground and marine vehicle developers. We would also like to afford MEMS technology developers an opportunity to present in some detail the results of their laboratory demonstrations. In particular, we want to give MEMS technology developers in areas of early and high payoff to the gas turbine engine technology base an opportunity to to present the broad range of data needed to substantiate the claim, “The device works!”

What do you mean when you say “It works”? We urgently need your input for the workshop to be held August 2–4 at IDA.

Construction of Workshop Agenda

- Recommendations and Suggestions For
  - Goals and Objectives: Topics, Speakers
  - Technology Objectives: Topics, Demos
  - General Participants

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GLOSSARY

ACTD	advanced concept technology demonstration
APU	auxiliary power unit
ATD	advanced technology demonstration
DARPA	Defense Advanced Research Projects Agency
IDA	Institute for Defense Analyses
MEMS	microelectromechanical systems
NASA	National Aeronautics and Space Administration
NDI	nondestructive inspection
R&D	research and development
RF	radio frequency
T&E	test and evaluation
UAV	uninhabited aerial vehicle

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2000	Final — February – June 1999

4. TITLE AND SUBTITLE
MEMS Technology Transition Opportunities for Gas Turbine Engines

5. FUNDING NUMBERS
DASW01 98 C 0067
DARPA Assignment DA-2-205

6. AUTHOR(S)
Forrest R. Frank

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
1801 N. Beauregard St.
Alexandria, VA 22311-1772

8. PERFORMING ORGANIZATION REPORT NUMBER
IDA Paper P-3482

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Advanced Research Projects Agency
3701 North Fairfax Drive
Arlington, VA 22210

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 180 words)***

This paper is based on a workshop conducted jointly with the Propulsion Directorate of the Air Force Research Laboratory, with participants drawn from the Navy, Army, and NASA gas turbine engine development community. The purpose of the workshop was to assist the Defense Advanced Research Projects Agency (DARPA) in identifying transition or insertion opportunities for microelectromechanical systems (MEMS) from the laboratory to the field. The presentation offers highlights from the workshop, links major technical challenges, assesses technology transition opportunities, lists barriers to technology transition, and discusses future prospects for MEMS in turbine engines.

14. SUBJECT TERMS
MEMS, gas turbine engines, technology transition

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR